



# Advanced Hall Electric Propulsion for Future In-Space Transportation

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# **ADVANCED HALL ELECTRIC PROPULSION FOR FUTURE IN-SPACE TRANSPORTATION**

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## **ABSTRACT**

The Hall thruster is an electric propulsion device used for multiple in-space applications including orbit raising, on-orbit maneuvers, and de-orbit functions. These in-space propulsion functions are currently performed by toxic hydrazine monopropellant or hydrazine derivative/nitrogen tetroxide bi-propellant thrusters. The Hall thruster operates nominally in the 1500 s specific impulse regime. It provides greater thrust to power than conventional gridded ion engines, thus reducing trip times and operational life when compared to that technology in Earth orbit applications. The technology in the far term, by adding a second acceleration stage, has shown promise of providing over 4000s Isp, the regime of the gridded ion engine and necessary for deep space applications. The Hall thruster system consists of three parts, the thruster, the power processor, and the propellant system. The technology is operational and commercially available at the 1.5 kW power level and 5kW application is underway. NASA is looking toward 10 kW and eventually 50 kW-class engines for ambitious space transportation applications. The former allows launch vehicle step-down for GEO missions and demanding planetary missions such as Europa Lander, while the latter allows quick all-electric propulsion LEO to GEO transfers and non-nuclear transportation human Mars missions.

## **TECHNOLOGY DESCRIPTION HALL THRUSTER OPERATION**

The Hall thruster is an electric propulsion device used for orbit raising, on-orbit maneuvers, and de-orbit functions which are currently performed by hydrazine monopropellant or hydrazine derivative/nitrogen tetroxide bi-propellant thrusters. The Hall thruster nominally operates in the 1500 s specific impulse regime. It provides greater thrust to power than the conventional gridded ion engines, thus reducing trip times and requiring lower operational lifetimes when compared to that technology in Earth Orbit applications. The technology in the far term, by adding a second acceleration stage, has shown promise of providing over 4000s Isp, the regime of the gridded ion and necessary for deep space applications.

The Hall thruster system consists of three parts, the thruster, the power processor, and the propellant system. A simplified schematic diagram of a Hall thruster is presented in figure. 1 and an overview of the underlying physics is available in Ref. 1. The typical propellant for a Hall thruster is a high molecular weight inert gas such as xenon. A power processor is used to generate an electrical discharge between a cathode and an annular anode through which the majority of propellant is injected. A critical element of the device is the incorporation of a radial magnetic field, which serves to impart a spin to the electrons coming from the cathode and to retard their flow to the anode. The spinning electrons collide with the neutral xenon, ionizing it. The xenon ions are then accelerated from the discharge chamber by the electric potential maintained across the electrodes by the power processor. The velocity of the exiting ions, and hence the specific impulse, is governed by the voltage applied by the discharge power supply and is typically 15,000-16,000 m/s at 300 V. A sample Hall electric thruster is shown in figure 2.

## **HISTORICAL DEVELOPMENT**

As with the majority of electric propulsion devices, a great deal of early research and technology development was accomplished in the 1960's in both the United States and in the Soviet Union. At that time, high erosion rates and low performance led to the cessation of research on Hall thrusters in the US, in favor of the development of gridded ion accelerators. This effort culminated with the successful flight

demonstrations of ion systems on SERT 1 in 1964 and SERT 2 in 1970. In the Soviet Union, the opposite approach was taken. With the inability of attaining long life with low grid erosion, the Hall thruster efforts became the primary focus of development in the Soviet Union. In 1971 aboard a METEOR spacecraft, the first Hall thruster was flown. Over the next two decades several dozen 0.66 kW SPT-70 thrusters were used operationally in space. These flights and Russian advances in Hall thruster technology went virtually unnoticed by the rest of the electric propulsion community until approximately 1990.

## HALL ACCELERATOR

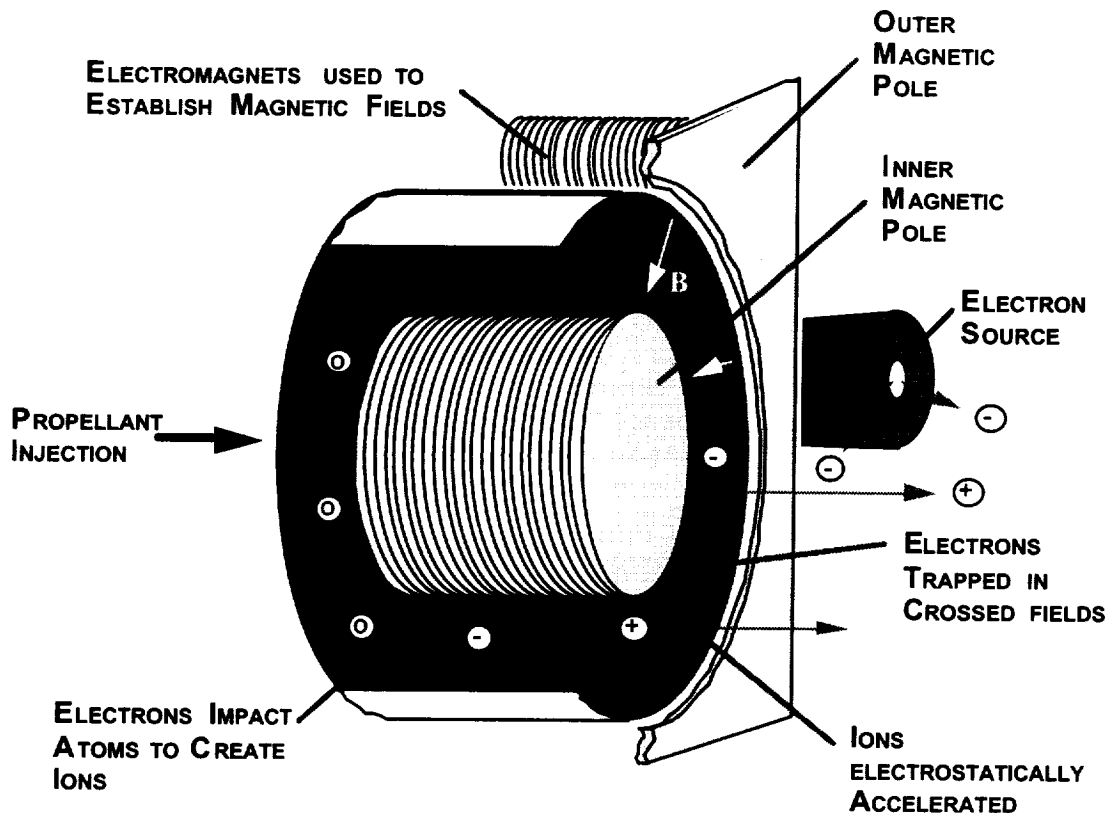
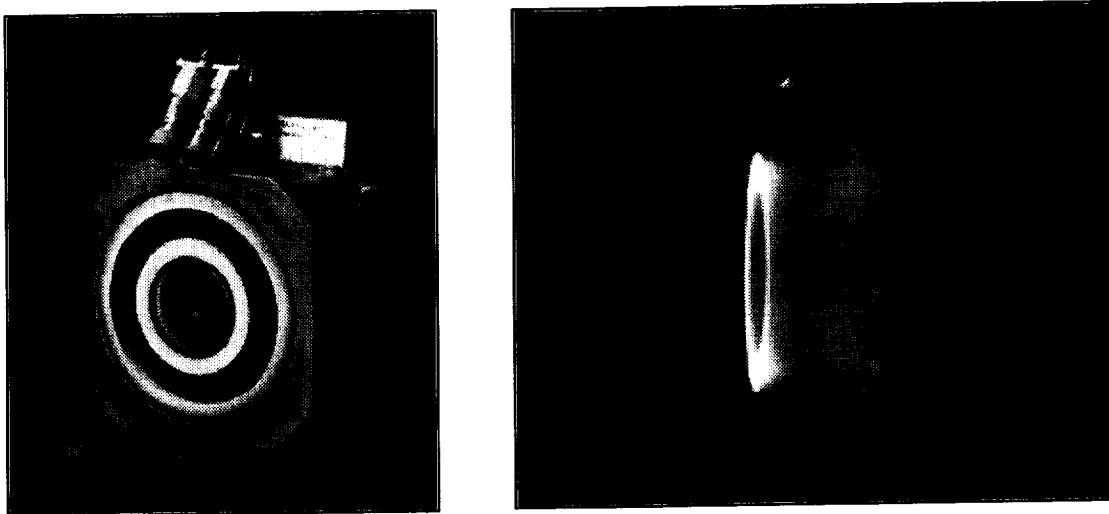


Figure 1.—Hall Thruster Operation.

At that time two events occurred simultaneously, an increase in openness between the USSR and the US and a reconfiguration of the SDIO space architecture to focus on small low Earth orbit (LEO) spacecraft. The SDIO recognized the value of advanced propulsion and quickly took the lead in reaching out to the electric propulsion community in the USSR. After the evaluation of data provided by the USSR on the Stationary Plasma Thruster, the SDIO sponsored a team of US government specialists from the Jet Propulsion Laboratory, NASA Glenn Research Center, and USAF Phillips Laboratory to visit two laboratories in the USSR in 1991. This group worked jointly with Russian specialists to determine if the technology had promise for incorporation on US spacecraft. The team was given unprecedented access to the yet not flight proven 1.35 kW SPT-100 thruster (Fig. 2). Testing was performed at both the Scientific-Research Institute of Thermal Processes (NIITP) (now Keldysh Research Center (KeRC)), Moscow, Russia and the Construction Bureau "Fakel", Kaliningrad, Kaliningrad Region, Russia. Under the Soviet system NIITP had responsibility for implementation of the government electric propulsion program, similar in function to a NASA laboratory, while Fakel was responsible for the production of flight thrusters, similar to a US commercial rocket company. Also participating in the evaluation were representatives from the academic community including A. Morozov, from the Kurchatov Atomic Energy Institute, responsible for the initial design of the Stationary Plasma Thruster. The findings of the team were that the technology appeared very promising; however, further evaluation in the US at specialized

NASA electric propulsion testbeds was recommended. Issues considered were performance at space representative conditions (very low vacuum chamber background pressures), impacts of the thruster on Western spacecraft, and the life of the device. The recommendations were followed, and an SPT-100 was purchased by the US government and delivered to NASA GRC for further evaluation.



**Figure 2.—Sample Hall Electric Thruster.**

Hall thruster technology work continued seamlessly under the successor agency to the SDIO, the BMDO. The BMDO has supported the development of joint US/Russian commercial ventures to provide Hall thruster technology to government and commercial users. Two of the earliest and strongest partnerships were International Scientific Products (ISP) (San Jose, CA and now part of Pratt & Whitney) and NIITP, and Space Systems/Loral (SS/L) (Palo Alto, CA) and Fakel. A third business relationship followed and included the Central Scientific Research Institute of Machine Building (TsNIIMash) and Olin Aerospace Corp. (OAC) (Redmond, WA) (now Primex Aerospace Co.) centering on the 1.35 kW Thruster with Anode Layer (TAL) version of the Hall thruster. Primex has since decided to pursue Hall technology using commercial funding with the Busek Co., based in Boston. TsNIIMash is now teamed with Boeing to provide the TAL technology.

Acting as the implementing agency for the BMDO in all electric propulsion activities, NASA GRC was tasked with bringing the technology to a level of development and demonstration acceptable to the US user community. The early vision was to take Russian thruster technology and combine it with US power electronics. The result when combined with specialized Russian and US propellant system components would be enabling technology for the worldwide spacecraft market.

The BMDO program consisted of three phases: (1) technology evaluation, (2) propulsion system design and ground demonstration, and finally (3) flight demonstration. The early technology evaluation program has helped the commercialization of the Fakel SPT-100 with baselined flights on future Space Systems/Loral spacecraft. The "Thruster-on-a-Pallet" ground demonstration program (RHETT1) demonstrated a compact, minimal spacecraft interface, joint US/Russian Hall thruster propulsion system centered on KeRC T-100 thruster, which piqued the interest of TRW. The culmination of the BMDO/NASA GRC program was the use of a low-power Hall thruster system operationally on the NRO STEx spacecraft under the NRL Electric Propulsion Demonstration Module (EPDM) program.<sup>2,3</sup> That multiagency effort resulted in the first use of a Hall thruster on a US spacecraft. The flight propulsion system hardware for that system was supplied by the NASA GRC through BMDO sponsorship under the RHETT2 program and consists of a TsNIIMash TAL D-55. The efforts over the last several years have established a significant industrial base in the US. Potential technology providers now include Atlantic Research Corp. (ARC), Boeing, Primex, and Pratt & Whitney.

# Hall Thruster

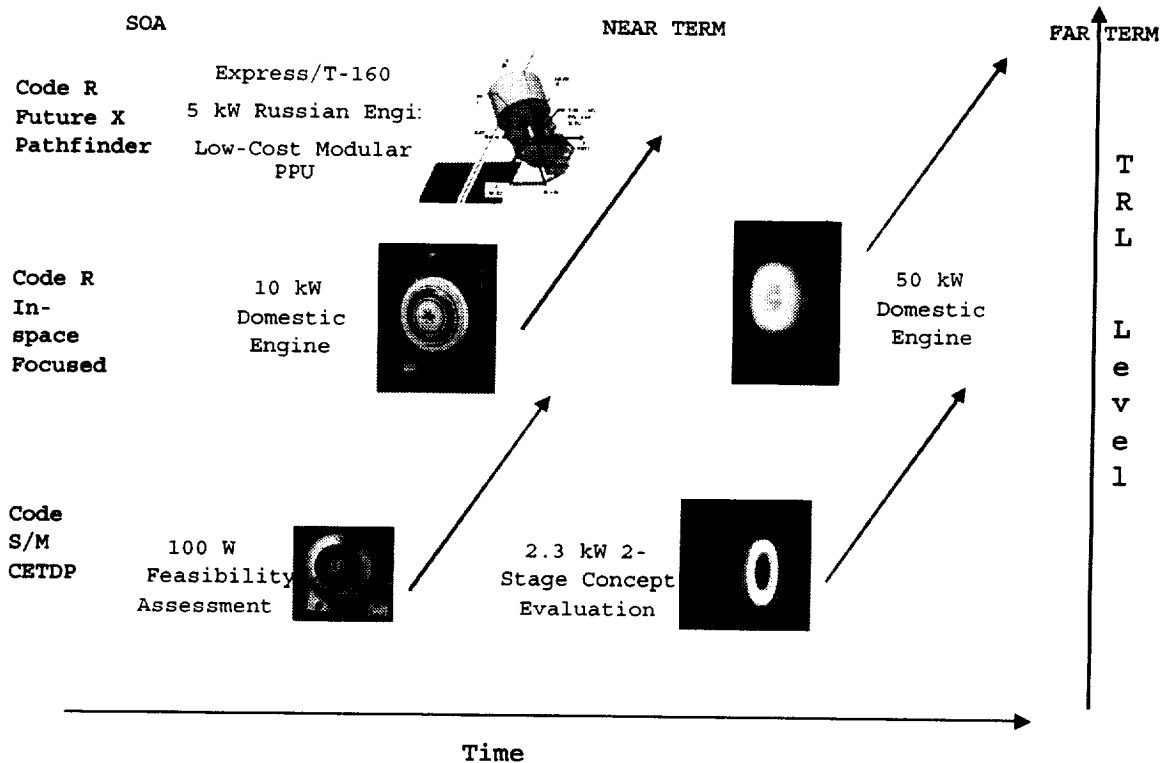


Figure 3.—Hall Thruster Development Roadmap.

## CURRENT/PLANNED PROGRAMS

The 1.5kW power level is appropriate for orbit-raising and maneuvering of mid-range LEO class spacecraft; however, larger LEO payloads and GEO spacecraft require higher thrust which equates to higher power electric propulsion systems. The 5 kW-class technology is near maturity. Industry has baselined the technology on next-generation commercial comsats for stationkeeping and orbit insertion, including SS/Loral's next generation comsat. The AF under IHPRT is supporting the development of the SPT-140 with ARC, including a high performance power processor at SS/Loral. NASA lessons learned from the RHETT2 development program included the need for low-cost power processing technology. The problem of acceptance of the technology for future flights hinges on the ability to change spacecraft platforms with little non-recurring cost. With that in mind NASA under both BMDO and NASA FutureX program sponsorship developed and ground demonstrated a revolutionary power processor technology on the Express program, which sacrificed performance (efficiency) for dramatic cost reductions. NASA partnered with TRW and Space Power Inc on the Express Project. NASA's recent development dollars have been devoted to 10kW domestic thrusters. The higher power is tailored as the first step in the space transportation cost reduction process. A 10 kW engine designed and built for NASA by Space Power Inc. has undergone performance testing and has also completed a 1000 hr erosion evaluation test. Used alone or combined with advanced chemical systems, at least a 2x increase in payload is possible to GEO and planetary missions, such as Europa Lander are enabled off Delta II-class vehicles. NASA is now embarking on a 50 kW class engine program for future space transportation needs. This class of engine provides the ability to do full LEO to GEO transfers in reasonable time periods, reduces launch requirements for large platforms such as Space Solar Power by a factor of 2, and enables a non-nuclear transfer technology for human Mars missions while decreasing boosters required. The 50 kW program will first consist of design options and a proof-of-concept build and test. Figure 3 presents the Hall thruster development roadmap. The benefits of Hall electric thruster technology are discussed next.

## IN-SPACE APPLICATIONS

### Earth Orbit In-Space Transportation

Several applications of Hall thrusters exist which allow great savings in transportation costs. These include LEO satellite constellations, combined chemical/electric GEO insertions, and all electric LEO to GEO. In most of the applications the Hall propulsion system is used cradle to grave; in-space delivery, operation maneuvers, and end-of-life disposal are all functions performed by the same Hall thruster propulsion system. In the following missions Hall thruster propulsion systems provide a cost benefit by using a smaller launch vehicle or by increasing the payload for the existing launch vehicle.

### LEO Satellites

The advantages of a Hall thruster system for a LEO constellation mission are shown by a sample use on a Globalstar-type constellation.<sup>4</sup> Comparing chemical, arcjets, Hall, and ion thrusters for the orbit raise and deorbit, the launch mass is varied by choosing different starting altitudes. The spacecraft breakdowns are shown in figure 4. The reduced mass of the Hall thruster system allows an extra satellite to be added to each Delta launch vehicle as shown in figure 5. This reduces the required Delta launch fleet by three launch vehicles (11 instead of 14). The orbit raise assumes a continuous circumferential thrusting spiral using the payload's power collection and storage systems. De-orbit is merely the reverse of the initial orbit raise. Hall thruster operations could be autonomous similar to those of STEX and Deep Space 1 NSTAR ion propulsion system.

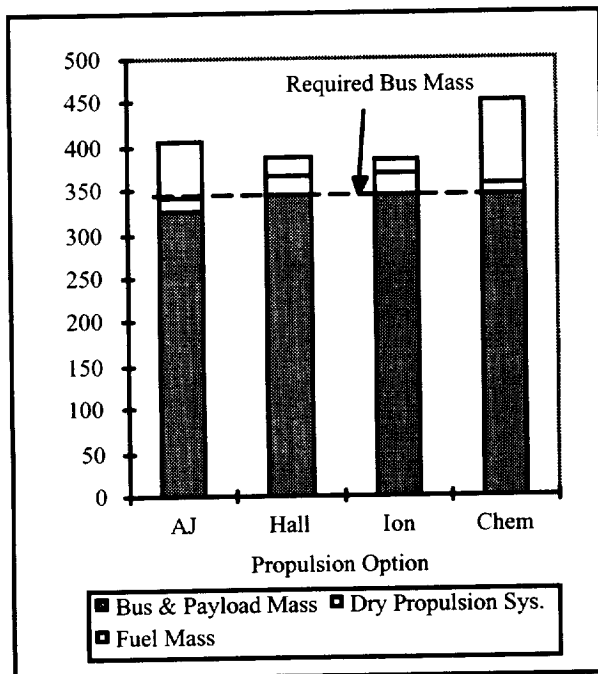


Figure 4.—LEO Satellite Masses.

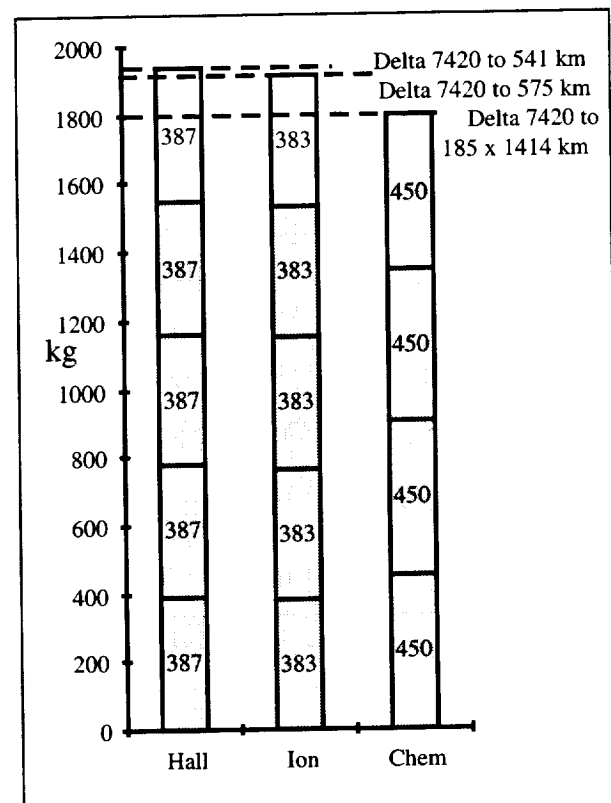


Figure 5.—Launch Mass Breakdown.

## GEO Satellites

### Near-Term Orbit Insertion

Hall thrusters are currently employed on several Russian geosynchronous communication satellites for stationkeeping duties. By enlarging the Hall thruster system to multiple 5 kW modules to take advantage of all the available satellite payload power (>20 kW in the near term), a short one to two month orbit insertion can be performed to significantly increase the payload mass (20 to 35%) as shown in figure 6.<sup>5,6</sup> The Hall thruster system outperforms a gridded ion system since it has an Isp performance closer to the optimal for the orbit insertion. (See references 5 and 6 for a complete explanation.) The delivery operations are as follows (Fig. 7): (1) launch to into a roughly geosynchronous transfer orbit by an expendable launch vehicle, (2) burn of the on-board apogee chemical system (which has some fuel off-loaded) to place the satellite into an inclined orbit with a perigee above the belts and apogee above GEO altitude, (3) Hall thruster operation to raise perigee, lower apogee, and change plane. The perigee height is set to avoid the damaging proton radiation belts. Several satellite providers plan on use of this orbit insertion technique.

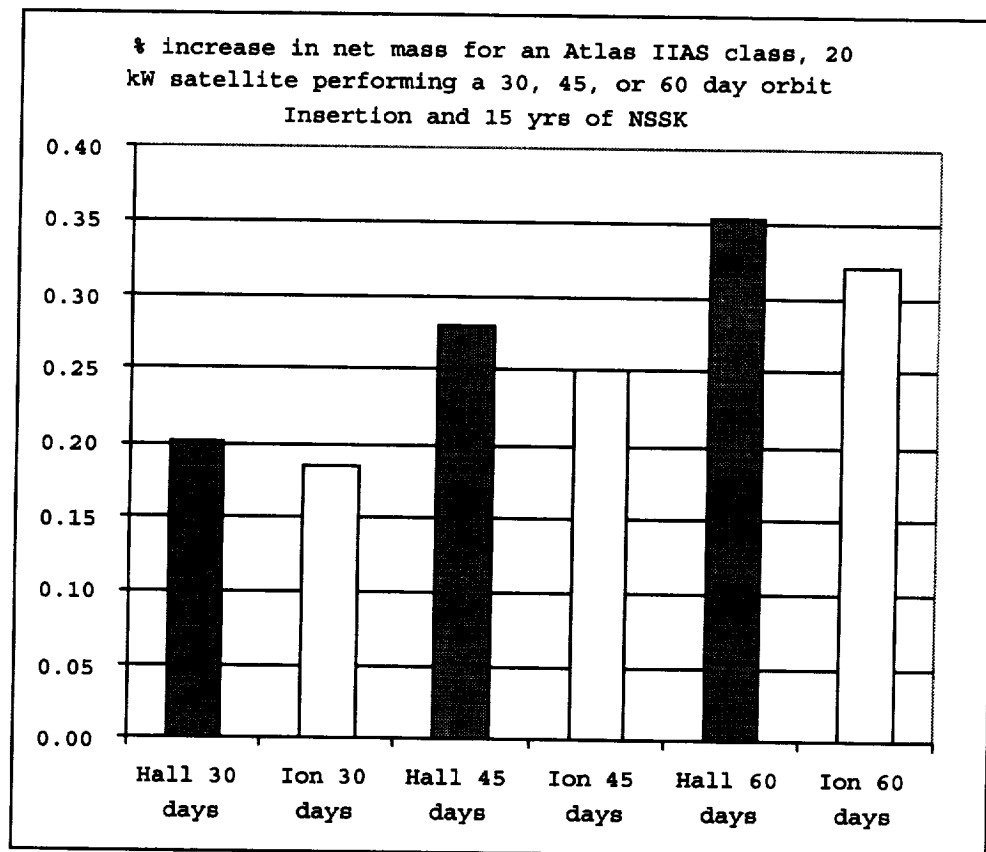


Figure 6.—GEO Payload Advantages with Hall Technology.

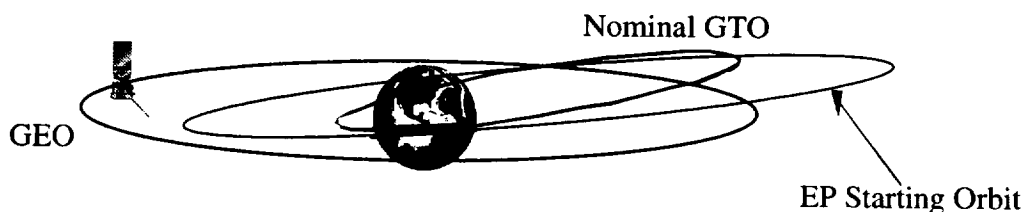


Figure 7.—Orbit Insertion Concept.



### Mid-Term Orbit Insertion

The next step is to remove the need for an upper stage to allow for an even greater benefit: doubling payloads for re-useable launch vehicles (RLVs) (no upper stage) or providing a launch vehicle step-down as shown in figure 8. For near term 40 kW payloads, the use of multiple 10 kW modules and a 60 day insertion can provide a step-down from an Atlas IIAR to a Delta 7920, approximately halving the launch costs. Payloads can be increased even more by allowing longer trip times. As shown in figure 9, the Hall thruster starting orbit is lowered even further than in the previous method.<sup>7</sup> The delivery operations are as follows (Fig. 9): (1) launch to LEO by an expendable launch vehicle or RLV without an upper stage, (2) burn of an expanded on-board apogee chemical system to place the spacecraft in an elliptical inclined starting orbit with apogee below GEO, (3) Hall thruster operation to raise perigee, apogee, and change plane. Part of the orbit raising operation will occur in the radiation belts, perhaps necessitating advanced radiation resistant arrays, although the exposure times should be a month or less.

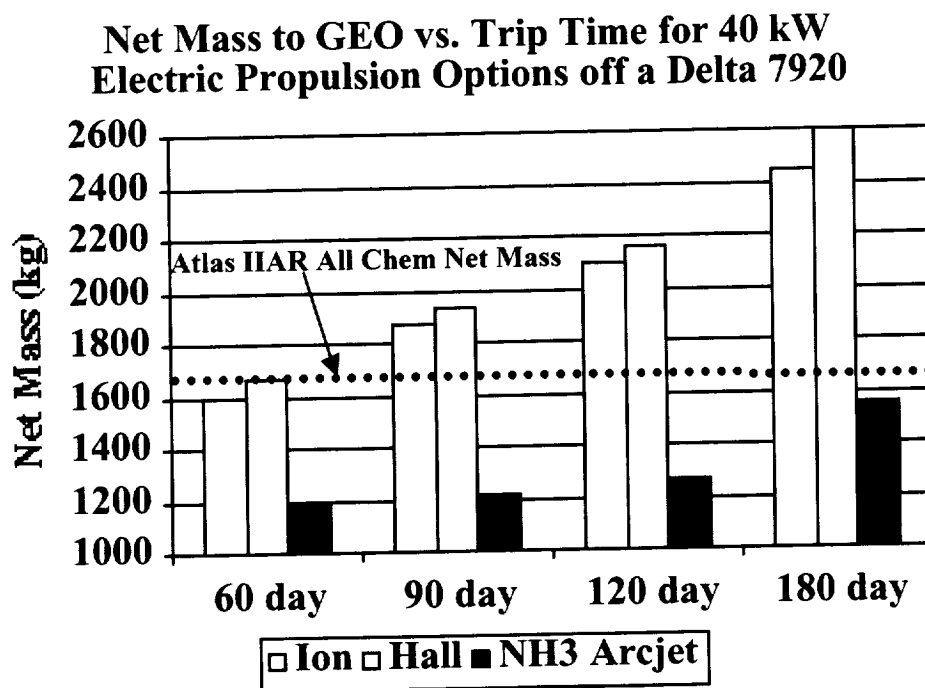


Figure 8.—Net Mass to GEO for 40 kW Hall Systems.

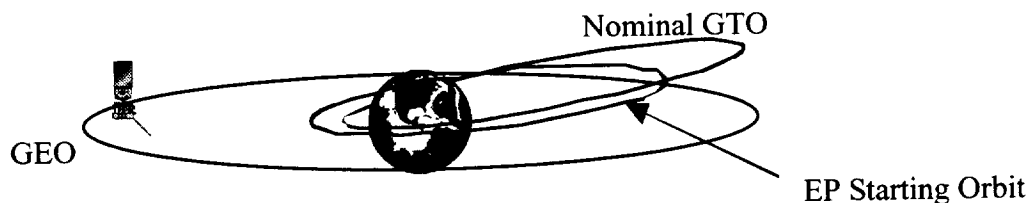


Figure 9.—All On-Board Propulsion, LEO to GEO Concept.

### Far-Term Orbit Raising

As power levels increase even more (50 kW class thrusters) GEO spacecraft should be able to transfer directly from LEO to GEO in a few months time. In these cases a payload increase of almost four times is possible. Again autonomous steering can be used to reduce operations costs.

Concepts delivering even larger platforms, such as space solar power satellites, have been studied.<sup>8</sup> 50 to 100 kW class Hall thrusters are the best electric propulsion system choice in order to reduce required launch fleet while minimizing delivery time. A comparison of Hall technology for the delivery of space solar power nodes is shown in figure 10. The Hall technology requires half the launch vehicles of a chemical in-space system and delivers the complete set of nodes from ground to GEO in less time based on a three launch per day limit.

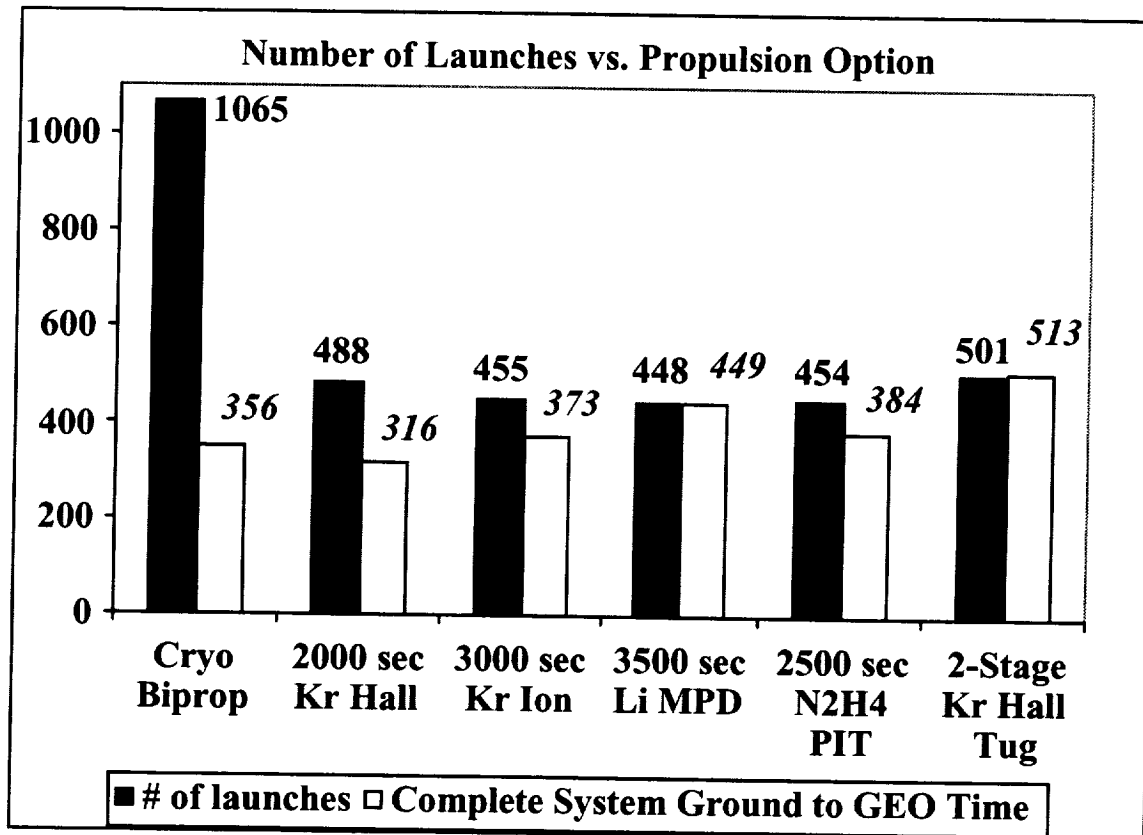


Figure 10.—Required Number of Launches and Total Ground to GEO Time for the 6000 MT Sun Tower Satellite.

### Interplanetary In-Space Transportation

#### Robotic Missions

Interplanetary missions can also benefit from Hall thrusters in some cases just by using them in Earth space to minimize the chemical escape stage requirements as suggested by Gefert and Hack.<sup>9</sup> As an example, a Europa Lander mission using two 10 kW Hall systems would allow a launch vehicle step-down from an Atlas IIAS to a Delta 7920 and only require a ~10% increase in trip time. The mission operations are as follows (Fig. 11): (1) launch to LEO by an expendable launch vehicle or RLV, (2) Hall thruster operation to raise only apogee, and place spacecraft in a highly elliptical orbit, just short of escape, (3) Burn of an on-board chemical system to place the spacecraft on an escape trajectory to the target, (4) capture is performed electrically, chemically or with aerobraking. Reuse of the Hall thruster systems may be possible for near planet operations.

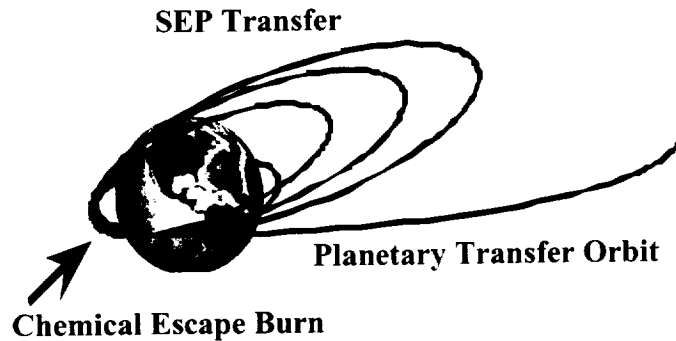


Figure 11.—Planetary Pump-Up Scenario.

### Piloted Missions

Piloted Mars missions can also benefit from same mission scenario as described above.<sup>9,10</sup> This savings in chemical escape propellant can approximately halve the needed launch vehicle fleet compared to all chemical and provides a non-nuclear option for manned Mars exploration. The pump-up operations are as follows: (1) launch to LEO of crew and cargo transports and a high power Hall thruster stage by several expendable launch vehicles, (2) Hall thruster operation to raise only apogee, and place spacecraft in a highly elliptical orbit, just short of escape (3) Utilize a crew taxi to man the Mars vehicle, (Hall stage separated at this point) (4) Burn of an on-board chemical system to place the space craft on an escape trajectory to the planet, (5) capture is performed with aerobraking. The Hall thruster stage (Fig. 12) is returned to LEO for other manned /cargo transfers.

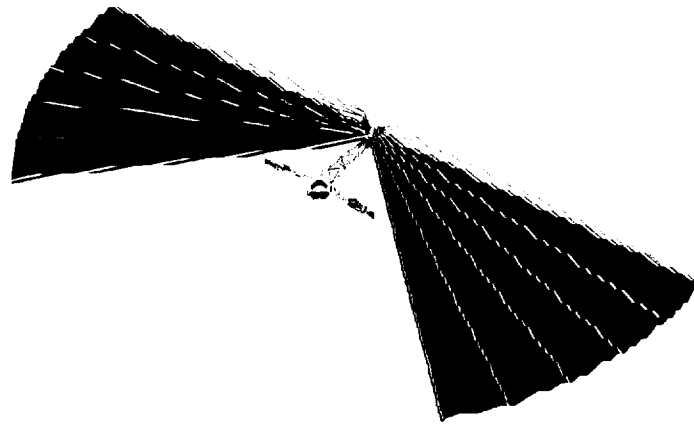


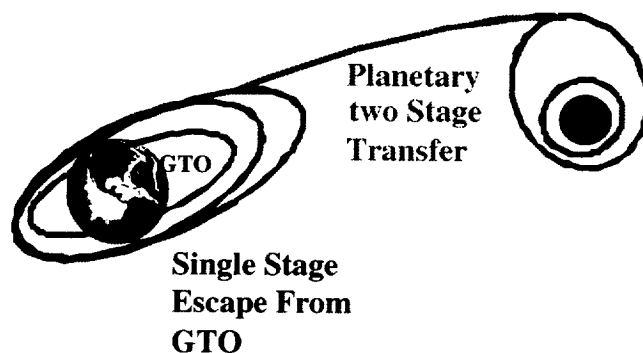
Figure 12.—HEDS Mars Hall Electric Stage.

### Multi-Mode Missions

Hall thrusters may also be operated in a wide range of specific impulse. The so-called 'Two Stage' Hall thruster could provide 'fast' lower planetary escape and maneuvering Isps (~1500 to 2000 sec) while also providing higher interplanetary transfer Isps (~3000 to 4000 sec). A similar concept suggested by Liefer utilized a set of separable Hall thrusters for the planetary escape and a set of gridded ion thrusters for the planetary transfer.<sup>11</sup> This concept allowed for a launch vehicle reduction. This two stage Hall thruster could provide highly flexible, 'on-the-fly' re-configurable planetary missions and ample maneuverability at the target and can provide up to 15% more payload and simplicity compared to the Liefer Ion and Hall thruster concept.<sup>12</sup> The mission operations are as follows (Fig. 13): (1) launch to GTO by an expendable launch vehicle, perhaps as a secondary payload, (2) Hall thruster single stage operation to raise only apogee, and place the spacecraft on an escape trajectory, (3) Hall thruster two stage operation for planetary space transfers, (4) capture is performed with the Hall system or with aerobraking

(5) Hall thruster single stage operation would provide systems near planet maneuvering depending on mission changing mission needs.

This variable Isp concept is also beneficial for earth orbit missions. Studies have shown that up to 100 kg of payload can be added to Atlas class geosynchronous spacecraft just by using a low Isp (~1700 sec) for the orbit insertion and a high Isp (~3000 sec) for the stationkeeping phase.



**Figure 13.—Interplanetary Concept with Two-Stage Hall Propulsion.**

## CONCLUSIONS

The Hall thruster is a non-toxic, electric propulsion device, which can be used for earth orbital and in-space applications including orbit raising, on-orbit maneuvers,  $\Delta V$  and de-orbit functions. Hall technology can also be beneficial for interplanetary applications by significantly reducing the chemical escape propellant. Hall technology is operational and commercially available at the 1.5 kW power level and the 5kW application is nearing use. NASA is looking toward 10kW power levels for in-space transportation applications such as no-upper stage RLV missions and launch vehicle step-down missions for geosynchronous and interplanetary missions. Eventually 50 kW-class engines will allow LEO to GEO orbit raising and piloted Mars exploration. The technology in the far term, by adding a second acceleration stage and/or higher voltage capability, has shown promise of providing over 3000s Isp, most beneficial for stationkeeping and deep space applications. By using both high and low Isp modes in one thruster even more payload mass can be delivered for multi-phase earth and interplanetary missions.

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